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AN EXPERIMENTAL STUDY OF THE ABSOLUTE TEMPERATURE SCALE. III

THE REPRODUCIBILITY OF THE STEAM POINT. THE  
EFFECT OF PRESSURE ON THE STEAM POINT

BY JAMES A. BEATTIE AND B. EDWIN BLAISDELL



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# AN EXPERIMENTAL STUDY OF THE ABSOLUTE TEMPERATURE SCALE. III.

## THE REPRODUCIBILITY OF THE STEAM POINT. THE EFFECT OF PRESSURE ON THE STEAM POINT

By JAMES A. BEATTIE AND B. EDWIN BLAISDELL

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### TABLE OF CONTENTS

	Page
1. Introduction.....	361
2. Apparatus and Materials.....	362
3. Experimental Procedure.....	365
4. Corrections.....	365
5. Effect of Variation of Conditions on the Indicated Temperature and Comparison of the Closed with the Open Hypsometer.....	367
6. Effect of Pressure on the Steam Point.....	368
7. Summary.....	373
8. Appendix.....	374

### 1. INTRODUCTION

The equation proposed by the Seventh General Conference of Weights and Measures<sup>1</sup> for expressing the relation between the temperature  $t_p$  of equilibrium between liquid water and its vapor at a pressure  $p$  standard mm. of mercury from 680 to 780 mm. is

$$t_p = t_{760} + 0.0367 (p - 760) - 0.000\ 023 (p - 760)^2, \quad (1)$$

where  $t_{760}$  is the normal steam point, 100° C. Smith, Keyes, and Gerry<sup>2</sup> treating their own data and those of the Reichsanstalt<sup>2</sup> proposed the relation

$$t_p = t_{760} + 0.0368535 (p - 760) - 0.000\ 020084 (p - 760)^2 + 0.000\ 000\ 01714 (p - 760)^3, \quad (2)$$

valid from 660 to 860 mm. to 0.001° C. or better. The disagreement between these two equations is rather serious, amounting to 0.0024° C.

<sup>1</sup> See G. K. Burgess, *Bur. Standards J. Res.*, **1**, 635 (1928).

<sup>2</sup> L. B. Smith, F. G. Keyes, and H. T. Gerry, *Proc. Am. Acad. Arts and Sci.*, **69**, 137 (1934); L. Holborn, K. Scheel, and F. Henning, *Wärmetabellen*, Vieweg (1919).

at 680 mm. and  $0.0044^{\circ}$  C. at 780 mm. We have made a study of the reproducibility of the steam point and of the effect of pressure on the steam point similar to that made for the sulphur point.<sup>3</sup> We have found that the steam point can be reproduced with a probable error of  $0.0003^{\circ}$  C. which corresponds to an error of about 0.000 000 012 in the determination of  $\alpha$  for a platinum resistance thermometer. Our relation for the effect of pressure on the steam point

$$t_p = 100. + 0.0368578 (p - 760) - 0.000\ 020159 (p - 760)^2 + 0.000\ 000\ 01621 (p - 760)^3, \quad (3)$$

is in agreement with Eq. (2) over the pressure range 660 to 860 mm. within our experimental error except at the high pressure end of the range.

Eq. (3) is in good agreement with the boiling points of water over the pressure range 680 to 800 mm. of mercury given in *Wärmetabellen*,<sup>2</sup> the maximum deviation being  $0.002^{\circ}$  C.

## 2. APPARATUS AND MATERIALS

We have for some years used a hypsometer constructed in accordance with the specifications of Mueller and Sligh<sup>4</sup> for calibrating platinum resistance thermometers at the steam point. When the barometric pressure is constant and near 760 mm. this hypsometer is quite satisfactory; we have at times made five successive calibrations of a thermometer with a probable error expressed in temperature of  $0.0006^{\circ}$  C. Atmospheric conditions permitting this precision are unusual.

The first closed hypsometer, constructed by Dr. John M. Gaines, Jr., was operated on the principle of the downward displacement of nitrogen and could be attached to the manostat<sup>3</sup> used for calibration at the sulphur point. In this apparatus the pressure could always be adjusted to within several millimeters of 1 standard atmosphere and the probable error of five calibrations expressed in terms of temperature was usually within  $0.0004^{\circ}$  C. The operation of the hypsometer depended on a nice balance of heat and cooling water input. A lack of balance was indicated by a fluctuation in the pressure and in the resistance of the thermometer.

Our final hypsometer, shown in Fig. 1, operated on the same principle as that used for realizing the sulphur point.

<sup>3</sup> J. A. Beattie, M. Benedict, and B. E. Blaisdell, *Proc. Am. Acad. Arts and Sci.*, **71**, 327 (1936).

<sup>4</sup> E. F. Mueller and T. S. Sligh, Jr., *J. Optical Soc. Am.*, **6**, 958 (1922).

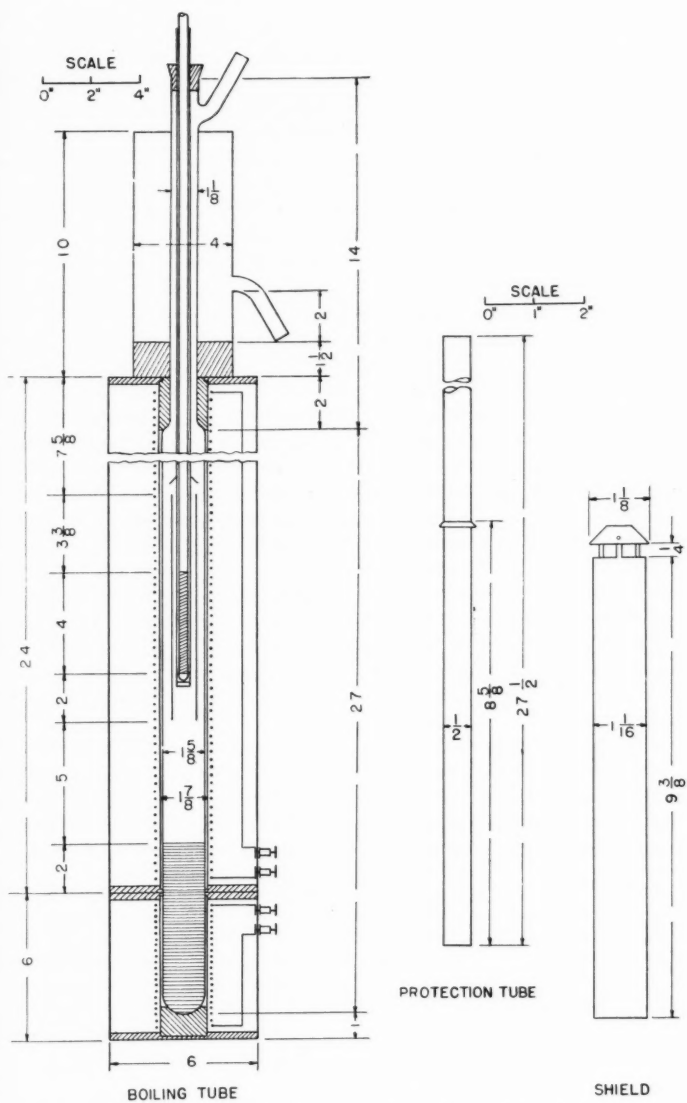


FIGURE 1. Details of the boiling apparatus. Dimensions are in inches.

*Thermometry.* The platinum resistance thermometers, Nos. 107 and 308, and the resistance bridge were the same as those used in the study of the sulphur point.<sup>3</sup>

*Barometry.* The comparator and scale, barometers, and manostat were the same as those used in the sulphur point work.<sup>3</sup> The manostat was filled with helium.

*Boiling Apparatus.* The construction of the heating unit and the insulating unit has been described before.<sup>3</sup> The lower end of the boiling tube was similar to that used for the sulphur point. To the upper end was sealed a tube 28.6 mm. (ca. 1 1/8 in.) inside diameter which extended into the insulating unit about 2 in., the annular space around the glass tube being packed with asbestos paper. Resting on top of the insulating unit was a pyrex cylinder about 10 in. long and 4 in. in diameter closed at the bottom by a rubber stopper. During a determination this cylinder was kept filled with crushed ice. The water from the melted ice ran off through a side arm about 2 in. from the top of the rubber stopper. The reason for decreasing the diameter of the boiling tube and packing it with an ice-water mixture is the necessity of having the water-vapor-helium boundary sharply defined and without convection mixing, and in a constant position in the tube.<sup>5</sup> In the tube which we used a shift in the position of the boundary of 1 mm. changed the volume of helium by about 0.5 cc., and since the volume of the manostat was approximately 90 liters, this shift of the boundary would affect the pressure by about 0.004 mm. The total variation of the pressure in the system over a period of several hours was less than 0.01 mm.

About 50 fine pyrex capillaries with sharp ends were placed in the boiling tube.

*Shielding.* The protection tube was of aluminum-manganese alloy, 1/2 in. outside diameter and 0.020 in. wall thickness. The bottom was welded vacuum-tight. The radiation shield, Fig. 1, and the method of suspending it was similar to that described before.<sup>3</sup> The shield was made from aluminum tubing 1 1/16 in. outside diameter and 0.020 in.

<sup>5</sup> When the diameter of the tube is too large in comparison with the temperature difference between the saturated vapor and the external temperature, the vapor-inert-gas boundary tends, we believe, to be conical in shape with the apex pointing upward and in the axis of the boiling tube. The heavier vapor then mixes with the gas due to the gravitational field, and the boundary shifts position thus causing a change in volume of the inert gas and a fluctuation in pressure and temperature. The same phenomenon was observed at the sulphur point when boiling tubes of 6 cm. diameter were used.

wall thickness, and blackened on its inner surface with black water-proof drawing ink.

*Water.* Distilled water was used. It was replaced from time to time. Gilfillan<sup>6</sup> found that the density of pure water obtained from Cambridge tap water is 2.3 parts per million less at 0° C. than that of pure water obtained from sea water. The total effect on the boiling point of the variation in isotopic composition of our water from sea water is less than 0.0001° C.

### 3. EXPERIMENTAL PROCEDURE

The disposition of the various units is shown in Fig. 1. The surface of the water was 5 cm. above the top of the heating unit. The condensation line of water vapor was 1 cm. above the top of the rubber stopper, and the mid-point of the thermometer was 33 cm. below the top of the insulating unit. No current was passed through the insulating unit. The protection tube was of aluminum-manganese alloy and one radiation shield was used.

At the start of a determination the upper cylinder was filled with ice, 3½ amperes passed through the heater, and the water vigorously boiled under reduced pressure to remove the air. The apparatus was flushed out twice with helium, and the 2-way stopcock then turned so as to connect the boiling tube to the manostat. The method of taking observations has been described before.<sup>3</sup>

### 4. CORRECTIONS

The equation<sup>3</sup> for reducing the observed height of mercury to standard mm. is

$$p \text{ (mm.)} = [L_1 - L_2 + \delta_1 - \delta_2 + 1.5 \times 10^{-6} (t - 20) (L_1 - L_2)] F - 0.001 + l_1 r_1 + l_2 r_2, \quad (4)$$

where

$L_1$  = scale reading in mm. corresponding to upper mercury surface

$L_2$  = scale reading in mm. corresponding to lower mercury surface

$\delta_1$  = calibration correction in mm. for  $L_1$

$\delta_2$  = calibration correction in mm. for  $L_2$

$1.5 \times 10^{-6} \text{ C.}^{-1}$  = linear coefficient of thermal expansion of the scale (invar.)

$t$  = scale temperature

$F$  = factor for reducing mercury height to standard gravity and 0° C.

<sup>6</sup> E. S. Gilfillan, Jr., J. Am. Chem. Soc., **56**, 406 (1934).

- 0.001 = net correction for capillary depression of mercury (bore of barometer tubing = 32 mm.)

$l_1$  = distance in mm. from the mid-point of the thermometer winding to the condensation line of water vapor, considered positive in the upward direction

$l_2$  = distance in mm. from the condensation line of water vapor to the lower mercury meniscus in the barometer, considered positive in the upward direction

$r_1$  = ratio of density of saturated water vapor at the pressure  $p$  to the density of mercury

$r_2$  = ratio of the density of helium at the pressure  $p$  and room temperature to the density of mercury.

The values of the ratios  $r_1$  and  $r_2$  are given in Table I. The error<sup>7</sup> introduced by use of the ideal gas law with the molecular weight 18.3 for saturated water vapor in the range 660 to 860 mm. is less than 0.2% in  $r_1$ . The head of water vapor is about 38 cm. which corresponds to a hydrostatic head of about 0.015 mm. of mercury.

TABLE I

VALUES OF THE RATIO ( $r_1$ ) OF THE DENSITY OF SATURATED STEAM AT THE SATURATION PRESSURE  $p$  TO THE DENSITY OF MERCURY, AND OF THE RATIO ( $r_2$ ) OF THE DENSITY OF HELIUM AT THE PRESSURE  $p$  AND ROOM TEMPERATURE TO THE DENSITY OF MERCURY.

Steam.					
	$\frac{18.3}{82.06 \times 13.5951 \times 760 (t + 273.1)}$		$\frac{p}{82.06 \times 13.5951 \times 760 (t + 273.1)}$		
$t = 100 + 0.0369 (p - 760) - 0.000\,020 (p - 760)^2 + 0.000\,000\,02 (p - 760)^3$					
$p$ (mm.)	660	710	760	810	860
$r_1 \times 10^6$	39	41	44	47	49
Helium.					
	$\frac{4.002\,p}{82.06 \times 13.5951 \times 760 \times 298.1}$				
$r_2 =$					
$p$ (mm.)	660	710	760	810	860
$r_2 \times 10^{6*}$	10	11	12	13	14

\*The error introduced by use of these values for room temperatures of 20° to 30° C. is less than  $0.5 \times 10^{-6}$  in  $r_2$ .

The correction of the resistance readings has been described before.<sup>3</sup>

<sup>7</sup> Compare F. G. Keyes, L. B. Smith, and H. T. Gerry, Proc. Am. Acad. Arts and Sci., **70**, 319 (1936).



5. EFFECT OF VARIATION OF CONDITIONS ON THE INDICATED TEMPERATURE AND COMPARISON OF THE CLOSED WITH THE OPEN  
HYPSOMETER

When the apparatus was first used the indicated temperature when reduced to 1 atmosphere pressure increased slowly with time and the appearance of the surface of the aluminum alloy protection tube changed from a bright to a dull, slightly pitted surface. After 30 hours of continuous operation the indicated temperature became constant and did not change during 50 hours of continuous use, and has not changed since.

The effect of varying certain conditions have been studied. The results may be summarized as follows:

(1) Replacing the water with fresh distilled water produced no effect greater than  $0.0003^{\circ}\text{C}$ .

(2) Increasing the current through the heating unit from 3 to 3.5 and then to 4 amperes raised the height of the condensation line a total of 1 cm. and changed the indicated temperature by  $+0.0002^{\circ}$  and  $-0.0004^{\circ}\text{C}$ ., respectively.

(3) The indicated temperature was  $0.0001^{\circ}\text{C}$ . higher without the shield than with the shield.

Taking into account the work done on the sulphur point, we feel that rather wide variations from our standard procedure are without effect greater than  $0.0003^{\circ}\text{C}$ . on the steam point.

We made a comparison of the temperatures indicated when the thermometers were placed in the closed hypsometer and in the open hypsometer of Mueller and Sligh. The results are given in Table II. Each entry for the closed hypsometer is the average of 5 determinations, the pressures being within 1 mm. of 760 mm.; each entry for the open hypsometer is the average of three determinations made on days when the atmospheric pressure was quite constant and within 2 mm. of 760 mm. The temperatures were computed from the known values of  $R_0$ ,  $\alpha$ ,  $\delta$ , for each thermometer and were then reduced to 760 mm. by Eq. (3). The average temperature indicated by the thermometer when in the closed hypsometer is taken to be  $100^{\circ}\text{C}$ . The average difference in the indicated temperature is about one-half the average deviation experienced in the use of the open hypsometer. We consider that this shows that there is no constant error inherent in the use of the closed hypsometer. The results also indicate that reproducibility of temperature in the closed hypsometer is about 4 times as satisfactory as that in the open hypsometer.

TABLE II

COMPARISON OF THE TEMPERATURES INDICATED IN THE CLOSED WITH THOSE INDICATED IN THE OPEN HYSOMETER

Thermometer No.	Temperature Indicated	
	Closed Hypsometer	Open Hypsometer
104	0.000 00 $\pm$ 0.000 30	-0.000 63 $\pm$ 0.001 20
107	0.000 00 $\pm$ 0.000 12	-0.001 03 $\pm$ 0.000 70
308	0.000 00 $\pm$ 0.000 15	+0.000 25 $\pm$ 0.000 88
Average	0.000 00 $\pm$ 0.000 19	-0.000 47 $\pm$ 0.000 93

Note: The average temperature reduced to 760 mm. by Eq. (3) indicated by each thermometer in the closed hypsometer is taken to be 100° C. For easy comparison 100 has been subtracted from each entry in the table.

#### 6. THE EFFECT OF PRESSURE ON THE STEAM POINT

Four runs each consisting of 8 to 10 determinations covering the approximate pressure range 660 to 860 mm. were made to determine the effect of pressure on the steam point. The two thermometers and two barometers used in the sulphur point work were employed. The results are given in Table III.

The value of  $\delta$  for each thermometer is the average value determined in the sulphur point work (see Table VI of reference 3). The computation of  $\alpha$  for each run and the average value of  $\alpha$  for each thermometer is given in Table IV. For the first approximation Eq. (2) for the effect of pressure on the steam point was used; this equation was so closely in agreement with our final equation that the second approximation did not change the value of  $\alpha$  by more than 1 or 2 units in the last significant figure. It will be noticed that the value of  $\alpha$  calculated for Run No. 4 differs by 1 unit in the last place from that used in Table III; unless more places are kept in  $\alpha$  and the observed temperature this difference cannot be prevented due to the way the numbers round off.

From the observed temperatures computed from the value of  $\alpha$  for each run and the observed pressures, columns (8) and (4) of Table III, the equation for the effect of pressure  $p$  standard mm. on the temperature  $t_p$ °C. (Int.) of equilibrium between water and its saturated vapor was found to be

$$t_p = 100 + 0.0368578 (p - 760) - 0.000\,020159 (p - 760)^2 + 0.000\,000\,01621 (p - 760)^3. \quad (3)$$

The constants were determined by the method of least squares. The international temperature  $t_p$  is about 0.001° C. lower than the *absolute*

temperature at 860 mm. and about  $0.001^{\circ}\text{C.}$  higher at 660 mm. The deviations of the calculated from the observed temperature are given in column (9) and are plotted in Fig. 2. In columns (10), (11), and (12) are given the results obtained when one value of  $\alpha$  is used for each thermometer. The deviations are plotted in Fig. 2. The average deviation is  $0.00043^{\circ}\text{C.}$  when a different value of  $\alpha$  is used for each run, and  $0.00054^{\circ}\text{C.}$  when one value of  $\alpha$  is used for each thermometer.

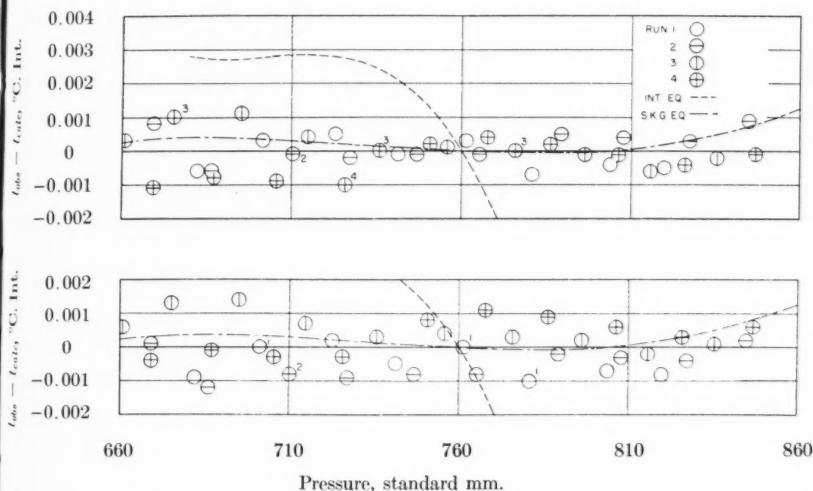


FIGURE 2. Plots of the observed temperatures minus the temperatures calculated by Equation 3 against the pressure. For the lower plot one value of  $\alpha$  was used for each thermometer; for the upper plot a different value of  $\alpha$  was used for each run. (S. K. G. = Smith, Keyes, and Gerry.).

The dotted line in Fig. 2 is the pressure calculated from the international equation, Eq. (1), minus that calculated from our equation, Eq. (3); the dot-and-dash line is the pressure calculated from the equation of Smith, Keyes, and Gerry, Eq. (2), minus that calculated from our equation.

We wish to thank Mr. Joseph Kaminsky for his help in making the computations.

We wish to thank the National Research Council for a grant from the Grants-in-Aid and the American Academy of Arts and Sciences for a grant from the Permanent Science Fund.

TABLE III  
THE EFFECT OF PRESSURE ON THE STEAM POINT  
 $t_{calc} = t_p = 100 + 0.0368578 (p - 760) - 0.000 020159 (p - 760)^2 + 0.000 000 01621 (p - 760)^3$   
 $t_{obs} = \frac{R_i - R_0}{\alpha R_0} + \delta \left( \frac{t_{obs}}{100} \right) \left( \frac{t_{obs} - 1}{100} \right)$

Run No.	Determination No.	Barometer	Pressure Standard mm.	Thermometer No.	R <sub>t</sub>	Different α used for each run			Average α used for each thermometer		
						R <sub>0</sub> , α, δ	t <sub>obs</sub> , °C. Int.	(t <sub>obs</sub> - t <sub>calc</sub> ) × 10 <sup>3</sup> °C. Int.	R <sub>0</sub> , α, δ	t <sub>obs</sub> , °C. Int.	(t <sub>obs</sub> - t <sub>calc</sub> ) × 10 <sup>3</sup> °C. Int.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	94	Right	819.842	107	35.13697	25.09091	102.1364	-0.5	25.09091	102.1361	-0.8
	95		803.642		35.08221	0.003921366	101.5711	-0.4	0.003921378	101.5708	-0.7
	96		780.865		35.00360	1.49251	100.7597	-0.7	1.49251	100.7594	-1.0
	97		761.445		34.93516		100.0535	+0.3		100.0532	0.0
	98		741.177		34.80201		99.2989	-0.1		99.2985	-0.5
	99		722.768		34.79420		98.5994	+0.5		98.5991	+0.2
	100		701.501		34.71395		97.7719	+0.3		97.7716	0.0
	101		682.128		34.63901		96.9993	-0.6		96.9990	-0.9
2	102	Right	669.411	308	35.53318	25.77524	96.4844	+0.8	25.77524	96.4837	+0.1
	103		686.300		35.60122	0.003921667	97.1670	-0.6	0.003921693	97.1664	-1.2
	104		710.274		35.69571	1.49176	98.1153	-0.1	1.49176	98.1146	-0.8
	105		727.132		35.76053		98.7660	-0.2		98.7653	-0.9
	106		746.892		35.83496		99.5133	-0.1		99.5126	-0.8
	107		765.185		35.90240		100.1905	-0.1		100.1898	-0.8
	108		789.444		35.98983		101.0687	+0.5		101.0680	-0.2
	109		807.675		36.05401		101.7135	+0.4		101.7128	-0.3
	110		827.162		36.12130		102.3897	+0.3		102.3890	-0.4
	111		844.621		36.18055		102.9853	+0.9		102.9846	+0.2

TABLE III—(Continued)  
THE EFFECT OF PRESSURE ON THE STEAM POINT

Run No.	Determination No.	Barometer	Pressure Standard mm.	Thermometer No.	$R_t$	Different $\alpha$ used for each run			Average $\alpha$ used for each thermometer		
						$R_0, \alpha, \delta$	$t_{obs}, ^\circ\text{C. Int.}$	$(t_{obs} - t_{calc}) \times 10^3, ^\circ\text{C. Int.}$	$R_0, \alpha, \delta$	$t_{obs}, ^\circ\text{C. Int.}$	$(t_{obs} - t_{calc}) \times 10^3, ^\circ\text{C. Int.}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
3	112	Right	835.436	107	35.18897	25.09093	102.6724	-0.2	25.09093	102.6727	+0.1
	113		815.760		35.12334	0.003921390	101.9947	-0.6	0.003921378	101.9951	-0.2
	114		796.220		35.05693	1.49251	101.3092	-0.1	1.49251	101.3095	+0.2
	115		775.742		34.98582		100.5753	0.0		100.5756	+0.3
	116		755.610		34.91435		99.8379	+0.1		99.8382	+0.4
	117		735.862		34.84266		99.0984	0.0		99.0987	+0.3
	118		714.856		34.76466		98.2939	+0.4		98.2942	+0.7
	119		695.082		34.68951		97.5190	+1.1		97.5193	+1.4
	120		675.203		34.61207		96.7207	+1.0		96.7210	+1.3
	121		660.644		34.55411		96.1234	+0.3		96.1237	+0.6
4	122	Left	669.273	308	35.53254	25.77522	96.4769	-1.1	25.77522	96.4776	-0.4
	123		687.241		35.60506	0.003921719	97.2045	-0.8	0.003921693	97.2052	-0.1
	124		705.553		35.67734	1.49176	97.9299	-0.9	1.49176	97.9305	-0.3
	125		725.756		35.75532		98.7126	-1.0		98.7133	-0.3
	126		750.652		35.84907		99.6539	+0.2		99.6545	+0.8
	127		767.640		35.91150		100.2808	+0.4		100.2815	+1.1
	128		786.414		35.97912		100.9600	+0.2		100.9607	+0.9
	129		806.188		36.04888		101.6609	-0.1		101.6616	+0.6
	130		825.930		36.11713		102.3467	-0.4		102.3474	+0.3
	131		846.893		36.18820		103.0610	-0.1		103.0617	+0.6
	Average deviation 0.43										Average deviation 0.54

TABLE IV

COMPUTATION OF  $\alpha$ 

$$t_p = 100 + 0.0368578 (p - 760) - 0.000\,020159 (p - 760)^2 + 0.000\,000\,01621 (p - 760)^3$$

$$\alpha = \frac{R_t - R_0}{R_0 \left[ t_p - \delta \left( \frac{t_p}{100} \right) \left( \frac{t_p}{100} - 1 \right) \right]}$$

Thermometer No. 107 308

 $\delta$  1.49251 1.49176

Run No.	Deter- mination No.	Ther- mometer No.	$t_p$	$t_p - \delta \left( \frac{t_p}{100} \right) \left( \frac{t_p}{100} - 1 \right)$	$\alpha$
1	96	107	100.7604	100.74896	0.003921346
	97		100.0532	100.05241	.0039213777
	98		99.2990	99.30939	.0039213601
	99		98.5989	98.61952	.0039213871
	$\alpha$ for Run No. 1				.003921366
2	105	308	98.7662	98.78438	.0039216577
	106		99.5134	99.52062	.0039216614
	107		100.1906	100.18775	.0039216635
	108		101.0682	101.05209	.0039216869
	$\alpha$ for Run No. 2				.003921667
3	114	107	101.3093	101.28950	.0039213869
	115		100.5753	100.56666	.0039213914
	116		99.8378	99.84022	.0039213935
	117		99.0984	99.11174	.0039213880
	$\alpha$ for Run No. 3				.003921390
4	125	308	98.7136	98.73254	.0039216805
	126		99.6537	99.65885	.0039217258
	127		100.2804	100.27621	.0039217355
	128		100.9598	100.94534	.0039217287
	$\alpha$ for Run No. 4				.003921718
$\alpha$ for Thermometer No. 107					.003921378
$\alpha$ for Thermometer No. 308					.003921693

## 7. SUMMARY

An apparatus for controlling and measuring the temperature of equilibrium between water and its saturated vapor is described. The reproducibility of the steam point is  $\pm 0.0003^\circ \text{C.}$ ; and rather wide variations on our standard procedure is without effect greater than  $0.0003^\circ \text{C.}$  on the indicated temperature.

The temperature  $t_p^\circ \text{C. (Int.)}$  of equilibrium between water and its saturated vapor at a pressure  $p$  standard mm. over the range 660 to 860 mm. is given by the relation

$$t = 100 + 0.0368578 (p - 760) - 0.000\,020159 (p - 760)^2 + 0.000\,000\,01621 (p - 760)^3.$$

The average deviation of 38 determinations from this equation is  $0.0004^\circ \text{C.}$

## 8. APPENDIX

*Effect of Errors in Determination of  $R_t$ ,  $R_0$ ,  $\alpha$ , and  $\delta$  on the Computed Temperature in the Neighborhood of the Steam Point.* In Table V are given the errors in the temperature computed from the Callendar equation due to errors in the determination of  $R_t$ ,  $R_0$ ,  $\alpha$ , and  $\delta$ . It will be noticed that errors in  $\delta$  have very slight effect on the temperature. The last column gives the effect of varying the temperature substituted into the last term of the Callendar equation on the computed temperature.

TABLE V

EFFECT OF ERRORS IN THE DETERMINATION OF  $R_t$ ,  $R_0$ ,  $\alpha$ ,  $\delta$  ON THE TEMPERATURE COMPUTED FROM THE CALLENDAR EQUATION IN THE NEIGHBORHOOD OF THE STEAM POINT

$$\Delta t = \frac{\Delta R_t}{R_0 \alpha D} \quad \Delta t = -\frac{(R_t - R_0) \Delta \alpha}{R_0 \alpha^2 D} \quad \Delta t = (1 - D) \Delta t^*$$

$$\Delta t = -\frac{R_t \Delta R_0}{R_0^2 \alpha D} \quad \Delta t = \left( \frac{t}{100} \right) \left( \frac{t}{100} - 1 \right) \frac{\Delta \delta}{D} \quad D = 1 - \left( \frac{2t}{100} - 1 \right) \frac{\delta}{100}$$

Assumed Constants:  $R_0 = 25.09081$        $\alpha = 0.003921378$        $\delta = 1.49251$   
 Assumed Variations:  $\Delta R_t = \Delta R_0 = 0.00010$        $\Delta \alpha = 0.000000010$        $\Delta \delta = 0.00010$   
 $\Delta t = 0.0010^*$

Temperature (°C. Int.)	Error $\times 10^3$ (°C.) in computed temperature due to				
	$\Delta R_t$	$\Delta R_0$	$\Delta \alpha$	$\Delta \delta$	$\Delta t^*$
104	1.033	-1.454	-0.269	0.004	0.016
102	1.032	-1.445	-.264	.002	.016
100	1.032	-1.436	-.259	.000	.015
98	1.031	-1.428	-.254	-.002	.014
96	1.031	-1.419	-.248	-.004	.014

\* This equation and column gives the effect on  $t$  produced by a variation in the temperature substituted into the term  $\delta \left( \frac{t}{100} \right) \left( \frac{t}{100} - 1 \right)$ .



